EXHIBIT 14

Energy Storage Materials
Volume 10, January 2018, Pages 246-267

Thermal runaway mechanism of lithium ion battery for electric vehicles: A review

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https://doi.org/10.1016/j.ensm.2017.05.013
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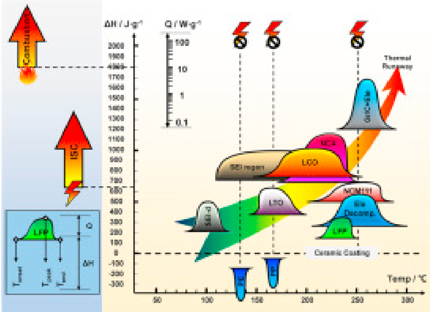
Abstract

The safety concern is the main obstacle that hinders the large-scale applications of lithium ion batteries in electric vehicles. With continuous improvement of lithium ion batteries in energy density, enhancing their safety is becoming increasingly urgent for the electric vehicle development. Thermal runaway is the key scientific problem in battery safety research. Therefore, this paper provides a comprehensive review on the thermal runaway mechanism of the commercial lithium ion battery for electric vehicles. Learning from typical accidents, the abuse conditions that may lead to thermal runaway have been summarized. The abuse conditions include mechanical abuse, electrical abuse, and thermal abuse. Internal short circuit is the most common feature for all the abuse conditions. The thermal runaway follows a mechanism of chain reactions, during which the decomposition reaction of the battery component materials occurs one after another. A novel energy release diagram, which can quantify the reaction kinetics for all the battery component materials, is proposed to interpret the mechanisms of the chain reactions during thermal runaway. The relationship between the internal short circuit and the thermal runaway is further clarified using the energy release diagram with two cases. Finally, a three-level protection concept is proposed to help reduce the thermal runaway hazard. The three-level protection can be fulfilled by providing passive defense and early warning before the occurrence of thermal runaway, by enhancing the intrinsic thermal stability of the materials, and by reducing the secondary hazard like thermal runaway propagation.

Graphical abstract



Introduction

The effort to save the modern society from energy crisis and environmental pollution has been made for years with challenges and hopes mutually emerging. Nowadays, the advanced technology can convert nuclear, wind or solar energy into electric energy with cleaner process and higher efficiency [1]. The coming era of electric energy is changing the energy storage system of vehicle from fossil fuels to electrochemical energy storage systems [2], thereby changing the propulsion system from engine to motor. The change of energy storage and propulsion system is driving a revolution in the automotive industry to develop new energy vehicle with more electrified powertrain system [3].

Electric vehicle (EV), including hybrid electric vehicle (HEV) and pure battery electric vehicle (BEV), is the typical products for new energy vehicle with more electrified powertrain system. The dramatic increase in the EV production in China since 2015, as shown in Fig. 1, is just an epitome of the rapid growth in the world EV market. Battery is the core component of the electrochemical energy storage system for EVs [4]. The lithium ion battery, with high energy density and extended cycle life, is the most popular battery selection for EV [5]. The demand of the lithium ion battery is proportional to the production of the EV, as shown in Fig. 1. Both the demand and the production of the lithium ion battery have exceeded 25GWh in 2016.

The range anxiety is one of the barriers for the widespread application of BEV, because it undermines the customers' confidence in using the BEV for longer trips as they did using traditional fossil-fueled cars [6]. The total range for current commercial BEV is approximately 150–200 km, e.g., 172 km for Nissan Leaf and 183 km for BMW i3. The limitation in the total range comes from the limited spaces for placing the battery pack onboard the EV. For instances, the total volume of the battery pack is approximately 220 L for a elecric car, and 400 L for a SUV. In order to extend the total range of a electric car or SUV, the volumetric energy density, with a unit of $Wh{\cdot}L^{-1}$, should be increased. Similarly, the gravimetric energy density also requires improvement for the range extension of the electric buses.

China has been developing the lithium ion battery with higher energy density in the national strategies, e.g., the "Made in China 2025" project [7]. Fig. 2 shows the roadmap of the lithium ion battery for EV in China. The goal is to reach no less than 300 $Wh\,kg^{-1}$ in cell level and 200 $Wh\,kg^{-1}$ in pack level before 2020, indicating that the total range of an electric car can be extended to 400 km or longer. To reach that goal, the cathode material may have to change from $LiFePO_4$ (LFP*) and $Li[Ni_{1/3}Co_{1/3}Mn_{1/3}]O_2$ (NCM111) to Ni rich NCM cathode like $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ (NCM622), $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NCM811), or Li-rich manganese-based oxide etc., whereas the anode material may have to change from carbon (C, including graphite) to a mixture of Si and C.

**The abbreviations in* Fig. 2 *are listed in* Table 1 *for references.*

However, the materials with higher energy density may have lower thermal stability [8], leading to safety problems, e.g., thermal runaway (TR). The utilization of NCM111 as cathode has already aroused safety concerns, not to mention

the Ni rich NCM cathode in the roadmap. The Chinese government ceased the use of NCM-based lithium ion battery in EV buses for several months in 2016, due to the occurrence of several TR accidents since 2015. The fear of using NCM or other cathode material with higher energy density comes from the lack of knowledge on the TR mechanisms. Although the NCM-based lithium ion battery was allowed to be utilized in EV buses after the more stringent compulsory test standards have been upgraded, it is found that many engineers and researchers are still not well equipped with sufficient knowledge on the battery TR mechanisms. Therefore, we feel it urgent to provide a review on the TR mechanisms of the lithium ion battery for EV. This review can provide guidance for engineers and researchers to conduct safety design of battery pack with higher energy density, and alleviate the fear of the battery safety problem.

Section snippets

Accidents with the lithium ion battery failure

Table 2 listed several selected accidents of lithium ion battery failure in last ten years [9], [10], [11], [12]. Most of lithium ion battery involved are for EV, whereas two of them are for aircraft (Boeing 787 Dreamliner). Battery fire accidents occurred more frequently since 2015, in accordance with the burst in the EV market in 2015.

The TR and TR-induced smoke, fire, and even explosion, are the most common features during the accidents of lithium ion battery. Smoke, fire and explosion are…

Mechanical abuse

Destructive deformation and displacement caused by applied force are the two common features of the mechanical abuse. Vehicle collision and consequent crush or penetration of the battery pack are the typical conditions for mechanical abuse.…

Overview of the chain reactions during thermal runaway

The mechanism of TR can be interpreted by the chain reactions as illustrated in Fig. 9. The chemical reactions occur one after another, forming chain reactions, once the temperature rises abnormally under abuse conditions. The Heat-Temperature-Reaction (HTR) loop is the root cause of the chain reactions. To be specific, the abnormal heat generation rises the temperature of the cell, initiates the side reactions, e.g., the SEI decomposition. Side reactions releases more heat, forming the HTR…

Reducing the hazard caused by thermal runaway

The reduction of the hazard caused by TR can be fulfilled in three levels, as shown in Fig. 14. The intrinsic safety, especially the anti-TR properties, of the lithium ion battery can be improved by material modification. Passive defense design can reduce the secondary damage under abuse conditions, whereas early detection algorithm is essential to warn the passenger of the coming fault. Once the TR occurred, countermeasures should be activated to reduce the secondary hazard, such as TR…

Summary and prospect

The safety concern is a main obstacle that hinders the large-scale applications of lithium ion batteries in EVs. Thermal runaway is the key scientific problem in the safety research of lithium ion batteries. This paper provides a

comprehensive review on the TR mechanism of commercial lithium ion battery for EVs. The TR mechanism for lithium ion battery, especially those with higher energy density, still requires further research.

Learning from typical TR accidents of lithium ion batteries for…

Acknowledgment

This work is supported by the National Natural Science Foundation of China under the Grant No. U1564205, and funded by the Ministry of Science and Technology of China under the Grant No. 2016YFE0102200.…

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